ontario hydro
research division

To: Mr. R.A. Coutts
Manager, Nuclear Operating Standards Department
Nuclear Generation Division

AN EVALUATION OF THE ERP DISPERSION MODEL USING DARLINGTON TRACER STUDY DATA

Report No 90-200-K

S.C. Wright
Environmental Science Section
Chemical Research Department

ABSTRACT

Site-boundary atmospheric dilution factors calculated by the atmospheric dispersion model used in the ERP (Emergency Response Planning) computer code were compared to data collected during the Darlington tracer study. In general, the comparison showed that the model underpredicted measured ground-level concentrations (glcs) for unstable atmospheric conditions and overpredicted the tracer glcs for stable atmospheric situations. Agreement between model results and tracer data was reasonable for neutral cases. The inclusion of a source height or building wake effect on vertical diffusion was necessary to avoid overpredicting dilution factors under stable conditions. An additional building wake correction for horizontal diffusion had only a small effect.

1.0 INTRODUCTION

1.1 Objectives

A comparison of results from the atmospheric dispersion model used in ERP (the Emergency Response Planning computer code) to data collected during the Darlington Tracer Study has been completed. ERP's atmospheric dispersion model is a generic one which is expected to be applicable for near ground level releases in flat, homogeneous terrain. The goal of this comparison was to obtain estimates of model uncertainty under a variety of conditions. Little information has been available about how local factors such as uneven terrain, large nearby buildings and a lakeshore setting may affect dispersion model performance. The objectives of the model evaluation described here were to:

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- report on model performance using Darlington Tracer Study data;
- identify meteorological scenarios, if any, which may lead to large error in model output; and
- determine whether model performance can be improved by correcting for site specific factors (building wake, light wind meander, effective release height).

This report provides background on ERP, the ERP dispersion model and the Darlington tracer study. A modification to the ERP dispersion model was made to include building wake effect and is also described. Model evaluation techniques are discussed briefly. Results of the comparison of model calculations with the field data are presented and reviewed.

1.2 Emergency Response Planning Code (ERP)

The computer code ERP was developed at Ontario Hydro (Serrador, 1986). It is used to estimate source term, to calculate atmospheric dispersion and to predict radiation doses. In the unlikely event of an accident, protective actions must be taken to ensure public safety. The Province of Ontario Nuclear Emergency Plan (1986) requires that projections of off-site radiation doses be made to allow timely decision-making on these protective actions. The primary use of ERP under the Provincial Plan is to provide dose projections. To estimate source term, ERP uses the calculation routine FASTDOS (Jamieson and Fluke, 1988). The atmospheric dispersion model which predicts transport and diffusion of emissions by atmospheric winds and turbulence is the Continuous Release Dispersion Model, CRDM.

1.3 Continuous Release Dispersion Model (CRDM)

CRDM is a surface similarity model. It calculates dilution factors for a near surface continuous release of non-reactive contaminants (Wright, 1986) as follows:

$$\frac{X(x,y,z)}{Q} = \frac{0.73\, e^{-\left(\frac{0.66z}{\bar{z}}\right)^{1.3}} e^{-\left(\frac{y^2}{2\sigma_y^2}\right)}}{\sqrt{2\pi}\ \bar{u}\ \bar{z}\ \sigma_y} \qquad (1)$$

where

X/Q is the dilution factor (s m^{-3});

x is the distance downwind of the emitter (m);

y is the distance crosswind from the emitter (m);

z is the distance above the ground (m);

$\bar{u}$ is the mean horizontal speed of the plume (m s^{-1});

$\bar{z}$ is the mean height of the plume material (m); and

σ_y is the lateral plume spread (horizontal standard deviation of the plume in the y direction) (m).

CRDM departs from the traditional Gaussian approach by using atmospheric surface layer parameters (surface roughness length - z_0, friction velocity - u_*, Monin-Obukhov length - L) to describe the vertical growth of the plume. This allows the variation of wind speed and turbulent diffusivity with height to be accounted for.

In CRDM, horizontal diffusion is assumed to be Gaussian (a justified assumption since conditions are expected to be reasonably homogeneous in the horizontal). Ontario Hydro's meteorological monitoring strategy (Fortune and Ogram, 1986) recommended that σ_y, the lateral plume spread, be related to a directly measurable observable, the standard deviation of wind direction, σ_θ (Pasquill, 1976). In the absence of σ_θ, an alternate method of determining σ_y may be used in CRDM. This method is based on stability class. The stability class is derived from L and z_0 (Golder, 1972), and the appropriate Briggs' (1973) formula for σ_y (as recommended by the National Working Group (1982)) is used.

For treatment of an elevated source height, h, CRDM assumes a virtual source located at a distance, x_0, upwind such that $\tilde{z} = h$ at the actual release point ($x = 0$). For a surface release, $x_0 = 0$.

1.3.1 Building Wake Modification

Before model calculations were carried out, CRDM was modified to include an option for building wake effect. This modification was based on the recommendation made (by the Ontario Ministry of the Environment) for modelling air quality due to releases from a location on or nearby a building (OME, 1986).

In modifying vertical diffusion for building wake effect, the emitted material is assumed to be mixed to a mean height ($\tilde{z}$) equal to half of the building height (H_B) in order to calculate a virtual source location. The plume is then assumed to originate from a virtual source at ground level located sufficiently far upwind of the building that

$$\tilde{z}(x = 0) = \frac{1}{2} H_B. \qquad (2)$$

This is similar to the method presently used in CRDM to account for elevated source height, except that $\tilde{z}=H_B$ in that case. Therefore it is not appropriate to include both a correction for elevated release height and building wake effect on vertical diffusion.

In the horizontal direction, it is assumed that the building-induced turbulence enhances the initial crosswind spread by factor proportional to one-fourth of the width of the building (W_B) exposed to the wind. The lateral plume spread is corrected as follows:

$$\sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_y^2} \qquad \text{where} \quad \sigma_{y_0} = \frac{1}{4} W_B \qquad (3)$$

1.4 Darlington Tracer Study

The Darlington tracer study (Ogram et al, 1989) was initiated to examine the effect of local site factors on short range atmospheric dispersion out to the site boundary, 1 to 2 km from the release point. The study was carried out at Darlington NGS during the winter of 1985 and the summer of 1986. During this study SF_6 tracer releases were made from the vacuum and powerhouse buildings under a variety of onshore wind conditions. Tracer concentrations were measured at or near the site boundary using an array of fixed samplers. Meteorological information was gathered from a network of instruments as well as site instrumentation.

2.0 MODEL EVALUATION

2.1 Methods

Although the review of the scientific components of models is of greater importance than a strict statistical evaluation (Hanna, 1988), tools to measure model performance are required. During the past ten years various statistically based procedures have been applied to atmospheric dispersion models. Generally, residual analysis (predicted minus observed concentrations), correlation coefficients and ratio methods constitute simple, yet viable model comparison techniques. For practical application, a combination of evaluation methods is best along with judgement by an experienced meteorological modeller (Hanna et al, 1982).

Comparison results for this model evaluation have been calculated using the methods described below.

2.1.1 Residual Analysis

As part of the present model evaluation, two basic residual measures which have been described and used in many other studies (Hanna, 1989 and Hanna, 1988 and Irwin and Smith, 1984 and Tikvart and Cox, 1985 and Cox and Moss, 1985) were used. The normalized or fractional bias, *FB* of the mean concentrations is

$$FB = \frac{2\,(\bar{C}_p - \bar{C}_o)}{\bar{C}_p + \bar{C}_o} \qquad (4)$$

where $\bar{C}_p$ is the mean predicted concentration and $\bar{C}_o$ is the mean observed concentration. The *FB* is the ratio of the difference between the predicted and observed concentration to the mean of the observed and predicted concentration. The *FB* indicates the tendency of the model to over- or underpredict and may vary between -2 and 2, with a desired value of zero. If the *FB* deviates significantly from zero, the modeller should review the assumptions used in the model.

The normalized mean square error, *NMSE* measures the scatter in the entire data set and is defined as:

$$NMSE = \frac{\overline{(C_p - C_o)^2}}{\bar{C}_o \bar{C}_p} \qquad (5)$$

In the case of the *NMSE*, the normalization by $\bar{C}_o\bar{C}_p$ is used so that the *NMSE* will not be biased by models that overpredict or underestimate.

2.1.2 Ratio Method

The ratio method has been described as a nonstandard statistical measure (Hanna, 1988). However, instead of considering the arithmetic difference between C_o and C_p, some experts use the ratio of C_p/C_o (Dickerson and Ermak, 1988). For example, the number of points between R=2 and R = 0.5 (where $R = C_p/C_o$) divided by the total number of points is the fraction of estimates that agree with observations to within a factor of two.

2.1.2.1 Geometric Mean Ratio and Standard Deviation

In this model evaluation study, the ratio of the predicted to the observed concentrations was found to cover a wide range. For these situations the application of the lognormal distribution can be most useful (eg, Hinds 1982). The geometric mean, *GM* is defined as:

$$\ln GM = \frac{\sum n_i \ln R_i}{N} \tag{6}$$

The geometric standard deviation, GSD is calculated by:

$$\ln GSD = \left[\frac{\sum n_i (\ln R_i - \ln GM)^2}{N - 1}\right]^{1/2} \tag{7}$$

2.2 Model Runs - Description

A number of CRDM-model runs were made to examine the effect of including corrections for building wake and release height. These scenarios were numbered I, II, III and IV (where I is the least conservative scenario and IV is the most conservative scenario) and are described in Table 1.

TABLE 1

MODEL SCENARIOS

Scenario	Description
I	Building Wake Effect Included (both vertical and horizontal diffusion are modified)
II	Building Wake Effect Included (only horizontal diffusion is modified) Release Height = 0 m
III	No Building Wake Effect, Release Height = H_B
IV	No Building Wake Effect, Release Height = 0 m

In addition, the meteorological sites used during the Darlington tracer study (see Figure 1) provided five different sets of wind speed data which were input to the CRDM model. Table 2 lists the sites and their descriptions and Table 3 summarizes the observed dilution factors as well as the wind speed data used as input. The observed dilution factors listed in Table 3 are one-hour averages.

The CRDM model also requires a surface roughness length to be input. The model default value of 0.4 m, which is characteristic of rural terrain, was used.

CRDM was run using data from each of the five meteorological sites in combination with scenarios I - IV. This resulted in a total of twenty distinct cases. For each of these cases, the maximum plume centreline dilution factors at the site boundary and the corresponding lateral plume spreads were calculated and compared to the measured data. The CRDM-computed dilution factors for each of the twenty cases are listed along with the observed data in Table 4.

2.3 Results and Discussion

2.3.1 Maximum Ground-Level Dilution Factors

Results for all twenty cases are shown in Figures 2 - 6 which are log-log plots of the measured versus CRDM-computed maximum ground-level dilution factors at the site boundary. Figure 2 shows measured versus CRDM-computed values for each scenario (I - IV) using wind speeds from the East Boundary Aerovane. Similarly, Figure 3 uses input data from the Inland Aerovane, Figure 4 the Microwave Tower Aerovane, Figure 5 the Hydraulic Studies Anemometer/Vane and Figure 6 the PIBAL at 50m. The following observations are made from Table 4 and Figures 2-6.

- Dilution factors predicted for scenarios I, II, III and IV are always in the following order IV $\geq$ II $\geq$ III $\geq$ I, ie, scenario IV is the most conservative (no building wake effect and release height = 0) and scenario I is the least conservative (building wake effect correction to vertical and horizontal diffusion).

- There is frequent underprediction by CRDM for the least conservative scenario I (building wake effect correction to vertical and horizontal diffusion).

- There is a large variation in the CRDM results compared to the measured data (especially for the most conservative scenario IV - no building wake effect and release height = 0). The maximum dilution factors measured during the Darlington tracer study exhibited a variation of little more than an order of magnitude. The CRDM-computed results range over three orders of magnitude.

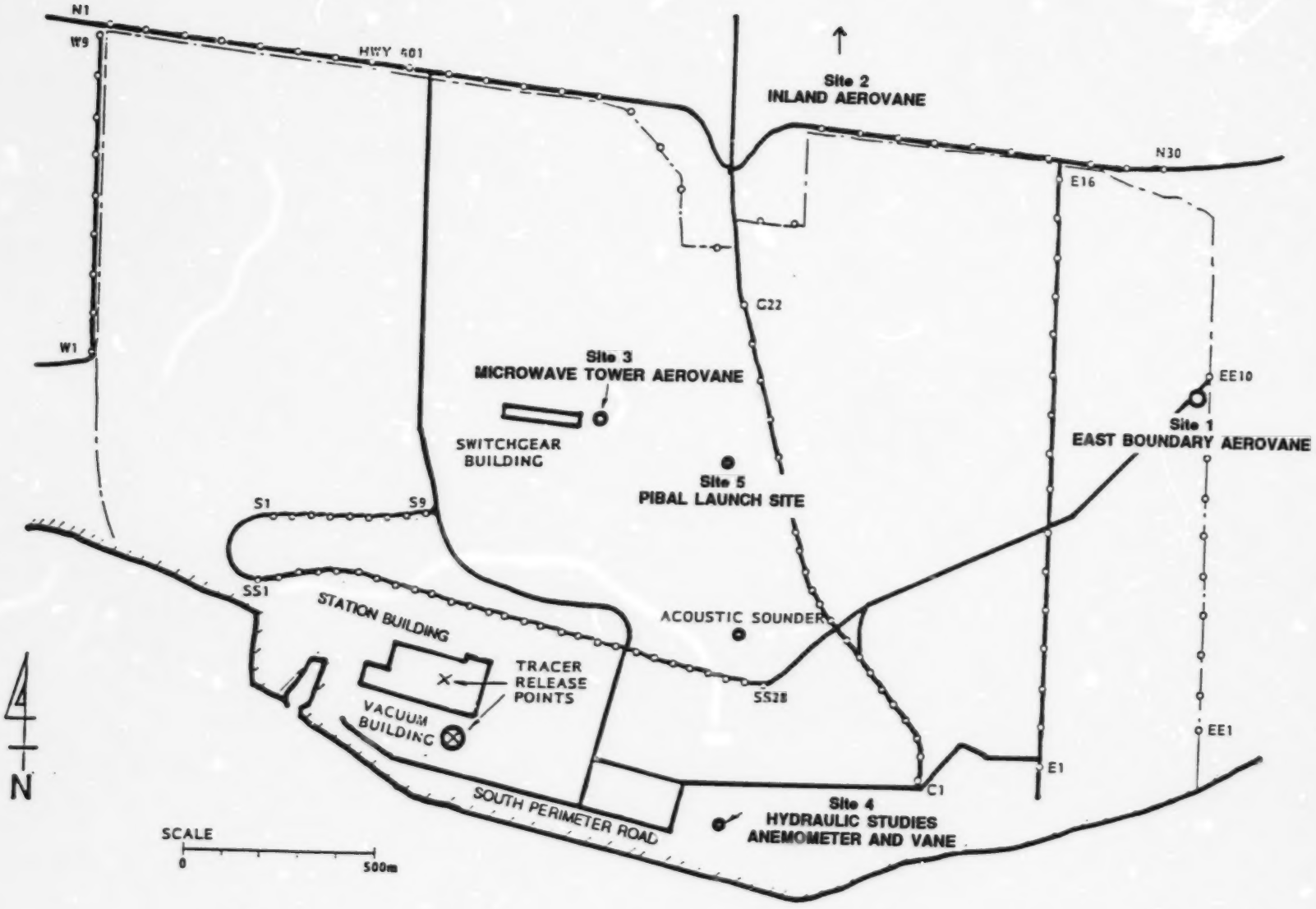


FIGURE 1

DARLINGTON TRACER STUDY

MET SITES

TABLE 2

METEOROLOGICAL SITES

Site	Description
1	East Boundary Aerovane (aerovane mounted at 8.2 m above grade at the eastern site boundary near the guardhouse, about 800 m inland)
2	Inland Aerovane (aerovane mounted at 8.2 m above grade about 6 km inland)
3	Microwave Tower Aerovane (aerovane installed at 50 m height on the microwave tower at the east end of the switchgear building)
4	Hydraulic Studies Anemometer and Vane (cup anemometer and wind vane on a 10 m mast located about 800 m east of the station building and 100 m from the lakeshore)
5	PIBAL (data at the 50m level from PIBAL-minisonde launched from a site about 350 m due east of the switchgear building)

TABLE 3

DARLINGTON TRACER STUDY OBSERVED DATA

DATE	TIME (EST)	DOWNWIND DISTANCE (m)	DILUTION FACTOR ($s\ m^{-3} \times 10^{-6}$)	WIND SPEED ($m\ s^{-1}$)				
				EAST BOUNDARY AEROVANE	INLAND AEROVANE	MICROWAVE TOWER AEROVANE	HYDRAULIC STUDIES ANEMOMETER/VANE	PIBAL 50m
181185	1100	1540	2.9		2.8			3.8
021285	1100	2010	0.9	14.2	8.3			
	1200	2000	1.1	12.8	8.3			
	1300	2000	1.7	9.7	6.4			
041285	1200	1820	2.0	1.5	1.5		1.5	2.2
	1300	1960	1.2	2.2	1.5		1.5	4.6
	1400	1860	0.86	2.5	1.5		3.3	3.1
	1600	1960	2.1	2.5	0.6		3.6	3.9
	1700	1820	2.5	1.9	calm		3.6	
	1800	1770	1.2	0.6	calm		2.5	
191285	1100	1570	2.1	5.8	4.4		8.3	6.5
	1300	1520	3.0	5.6	4.4		10.3	5.4
	1400	1510	2.1	5.3	4.2		7.8	6.5
	1500	1520	2.5	4.7	4.2		9.2	5.3
270586	1200	2030	3.3	2.8	3.1			1.7
290586	1000	1520	11.0	5.0	4.4	4.4	3.3	3.2
040686	0900	1770	4.6	2.2			1.5	2.4
	1000	1880	3.0	2.8		1.5	1.5	2.5
	1100	1610	7.1	4.2		2.5	1.5	3.2
	1200	1960	4.4	3.6		2.5	1.5	3.7
	1400	2000	5.2	5.6		5.6	4.4	3.1
	1500	2000	3.8	5.8		7.2	5.0	5.0
	1600	1880	4.0	6.7		8.9	5.8	7.5
160686	0900	1840	3.7	3.9		1.7		2.7
	1000	1670	4.4	6.7		3.3		4.6
	1100	1960	3.0	6.1		4.7		5.3
	1200	1680	3.4	6.4		10.3		5.3
	1300	2030	2.5	8.3		9.7		5.3
	1400	1900	2.9	6.9		12.2		6.5
260686	0900	2030	2.6			1.9	1.5	1.5
	1100	1400	4.4			1.9	1.9	1.5
	1200	1530	4.2			1.5	2.8	1.5

TABLE 4

OBSERVED AND CRDM-MODELLED DILUTION FACTORS

DATE	TIME (EST)	DOWNWIND DISTANCE (m)	OBSERVED DILUTION FACTOR ($s\ m^3 \times 10^4$)	CRDM-MODELLED DILUTION FACTOR ($s\ m^3 \times 10^4$)																			
				EAST BOUNDARY AEROVANE				INLAND AEROVANE				MICROWAVE TOWER AEROVANE				HYD STUDIES ANEMOMETER/VANE				PIBAL 50 m			
				I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
181185	1100	1540	2.9					1.9	3.6	2.0	3.8									1.7	3.4	1.9	3.7
021285	1100	2010	0.9	0.68	1.2	0.74	1.3	1.1	1.9	1.2	2.1												
	1200	2000	1.1	0.76	1.3	0.85	1.4	1.1	2.0	1.2	2.1												
	1300	2000	1.7	1.0	1.7	1.1	1.9	1.4	2.4	1.5	2.7												
041285	1200	1820	2.0	0.26	0.35	0.27	0.35	0.26	0.34	0.27	0.35					0.26	0.34	0.26	0.34	0.29	0.40	0.30	0.41
	1300	1980	1.2	0.53	0.82	0.56	0.86	0.23	0.31	0.24	0.32					0.22	0.29	0.23	0.30	0.76	1.3	0.81	1.4
	1400	1980	0.86	0.83	1.4	0.88	1.5	0.34	0.47	0.35	0.48					1.0	1.9	1.1	2.0	0.74	1.2	0.79	1.3
	1600	1980	2.1	6.1	30.0	7.3	36.0	6.5	150.0	10.0	200.0					5.1	15.0	6.1	18.0	6.2	36.0	7.3	43.0
	1700	1820	2.5	6.7	160.0	9.5	230.0	6.8	160.0	11.0	230.0					5.4	17.0	6.6	20.0				
	1800	1770	1.2	6.7	160.0	9.7	240.0	6.9	170.0	11.0	240.0					6.6	43.0	8.1	52.0				
191285	1100	1570	2.1	1.7	3.4	1.9	3.8	1.6	3.3	1.8	3.7					1.6	3.2	1.6	3.3	1.2	2.4	1.2	2.5
	1300	1520	3.0	1.8	3.8	2.0	4.2	1.8	3.7	2.0	4.2					1.4	2.9	1.5	3.0	1.3	2.7	1.4	2.8
	1400	1510	2.1	2.1	4.3	2.3	4.7	2.0	4.2	2.3	4.8					1.8	3.7	1.9	3.9	2.2	4.5	2.3	4.8
	1500	1520	2.5	2.5	5.2	2.8	5.7	2.5	5.3	2.9	6.0					1.6	3.2	1.7	3.5	2.8	5.9	3.1	6.4
270586	1200	2030	3.3	0.39	0.57	0.41	0.61	0.44	0.68	0.47	0.72									0.085		0.086	
290586	1000	1520	11.0	0.78	1.6	0.85	0.70	0.73	1.4	0.78	1.5	0.54	0.89	0.58	0.95	0.56	0.93	0.58	0.96	0.28	0.40	0.29	0.41
040686	0900	1770	4.6	0.22	0.31	0.23	0.32									0.084	0.12	0.085	0.12	0.12	0.15	0.12	0.16
	1000	1880	3.0	0.21	0.31	0.22	0.32					0.085	0.12	0.086	0.12		0.082		0.082	0.085	0.12	0.086	0.12
	1100	1610	7.1	0.61	1.1	0.67	1.2					0.14	0.18	0.14	0.18	0.10	0.12	0.10	0.12	0.25	0.35	0.25	0.36
	1200	1960	4.4	0.34	0.54	0.36	0.57					0.084	0.12	0.085	0.12					0.17	0.24	0.18	0.25
	1400	2000	5.2	0.54	1.0	0.58	1.1					0.41	0.69	0.43	0.73	0.44	0.76	0.46	0.081	0.15	0.21	0.16	0.21
	1500	2000	3.8	0.78	1.5	0.87	1.7					0.48	0.84	0.50	0.88	0.54	0.99	0.57	1.1	0.41	0.58	0.44	0.72
	1600	1880	4.0	1.0	2.0	1.1	2.2					0.97	1.9	1.1	2.1	0.99	1.9	1.1	1.2	0.67	1.3	0.71	1.3
160686	0900	1840	3.7	0.61	1.0	0.64	1.1						0.090		0.092					0.19	0.25	0.19	0.25
	1000	1670	4.4	1.1	2.1	1.2	2.4					0.25	0.35	0.26	0.36					0.49	0.78	0.53	0.83
	1100	1960	3.0	0.57	1.0	0.61	1.1					0.33	0.49	0.35	0.52					0.39	0.61	0.41	0.65
	1200	1680	3.4	1.1	2.1	1.2	2.4					1.1	2.1	1.3	2.4					0.60	1.0	0.64	1.1
	1300	2030	2.5	0.94	1.6	1.0	1.8					0.98	1.7	1.1	1.9					0.54	0.89	0.57	0.94
	1400	1900	2.9	0.94	1.7	1.0	1.9					0.95	1.7	1.1	1.9					0.46	0.74	0.49	0.78
260686	0900	2030	2.6									0.21	0.27	0.22	0.28	0.23		0.23		0.12	0.14	0.12	0.14
	1100	1400	4.4									0.19	0.24	0.19	0.24	0.36	0.29	0.37	0.30	0.14	0.17	0.14	0.17
	1200	1530	4.2										0.13		0.13	0.64	0.50	0.66	0.50	0.13		0.13	

10

90-200

EAST BOUNDARY AEROVANE

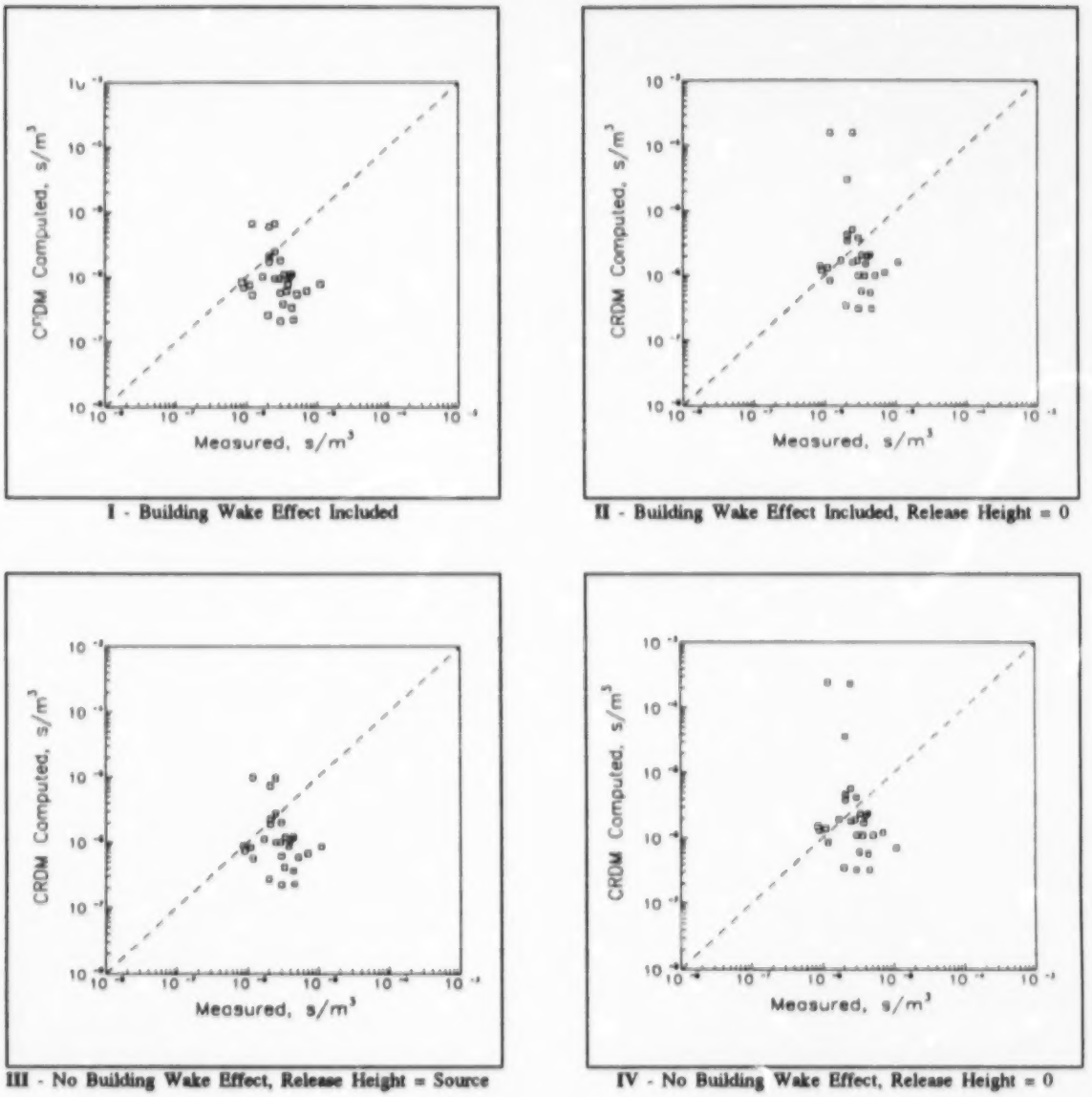
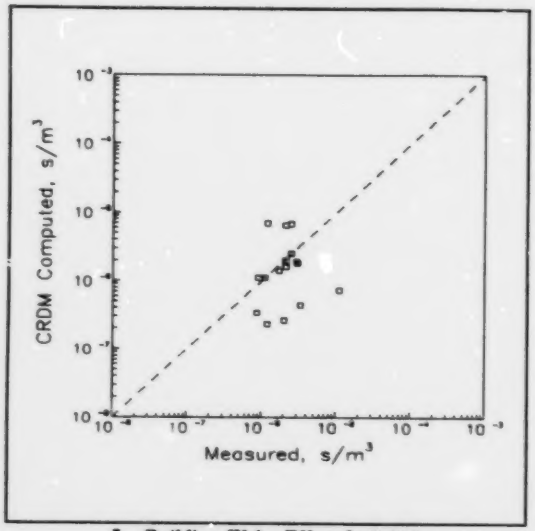

CRDM Computed, s/m³
Measured, s/m³
I - Building Wake Effect Included
II - Building Wake Effect Included, Release Height = 0
III - No Building Wake Effect, Release Height = Source
IV - No Building Wake Effect, Release Height = 0

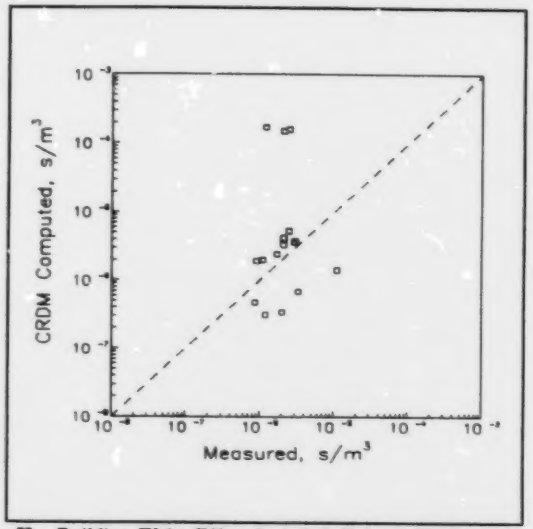
Figure 2

Log-Log plots of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **East Boundary Aerovane**

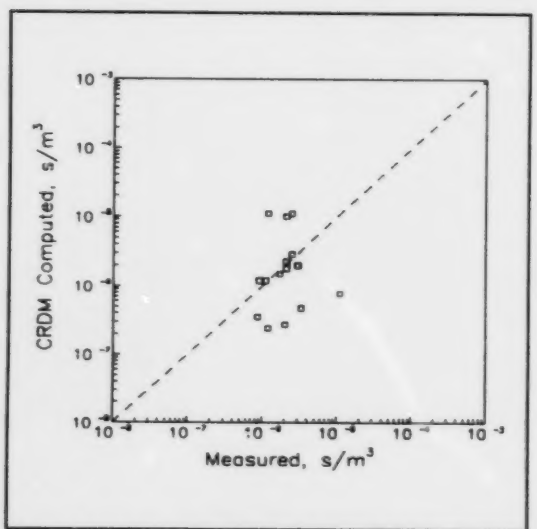
INLAND AEROVANE



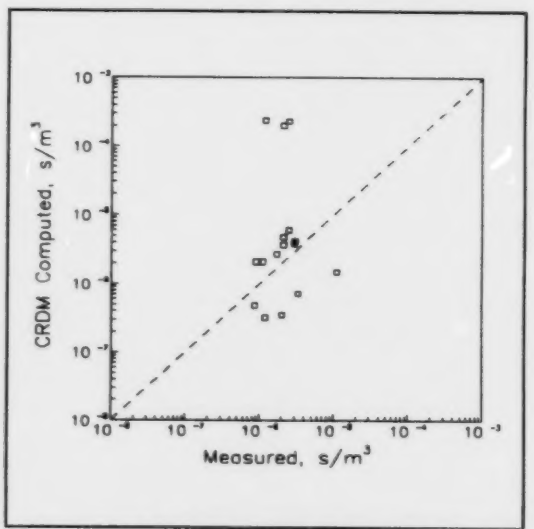
I - Building Wake Effect Included



II - Building Wake Effect Included, Release Height = 0



III - No Building Wake Effect, Release Height = Source



IV - No Building Wake Effect, Release Height = 0

Figure 3

Log-Log plots of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Inland Aerovane**

MICROWAVE TOWER AEROVANE

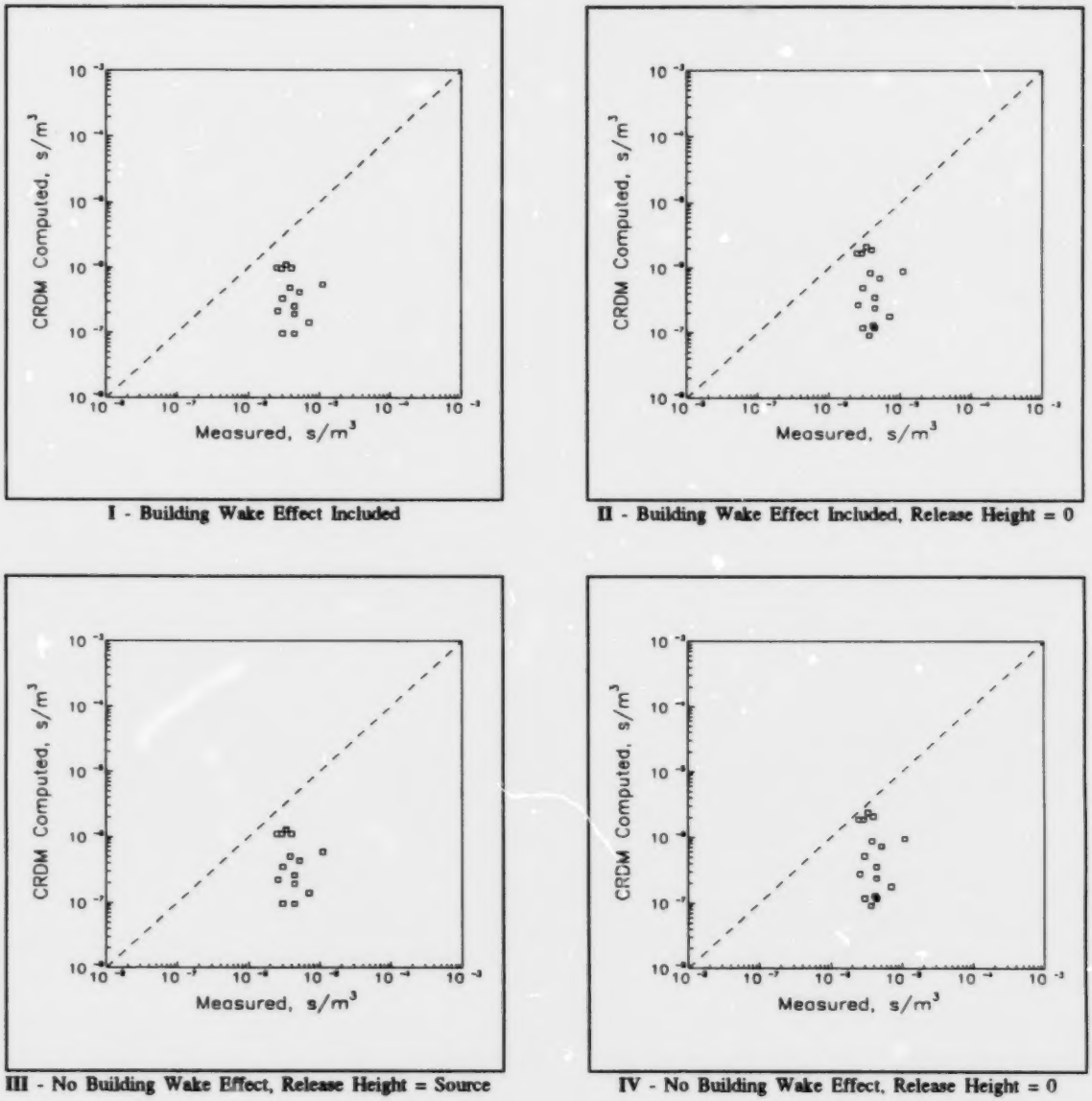
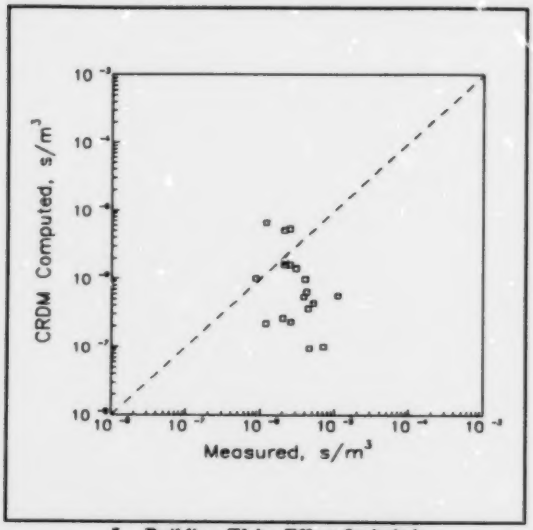

CRDM Computed, s/m³
Measured, s/m³
I - Building Wake Effect Included
II - Building Wake Effect Included, Release Height = 0
III - No Building Wake Effect, Release Height = Source
IV - No Building Wake Effect, Release Height = 0

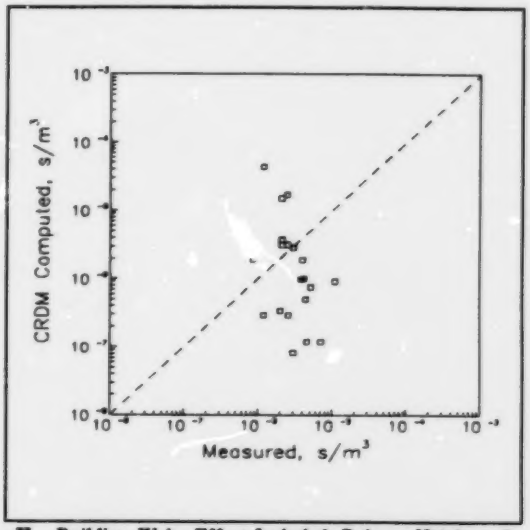
Figure 4

Log-Log plots of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Microwave Tower Aerovane**

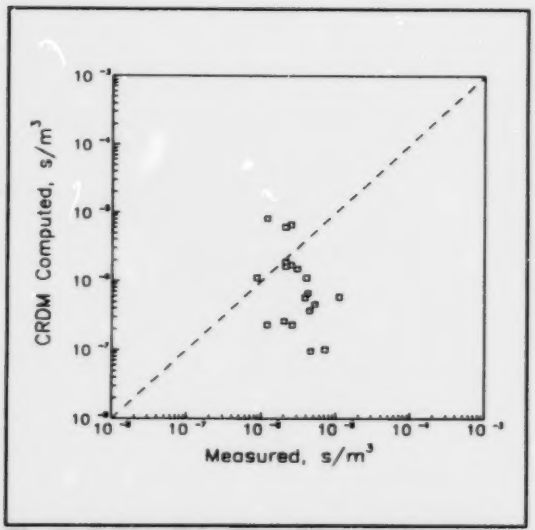
HYDRAULIC STUDIES ANEMOMETER/VANE



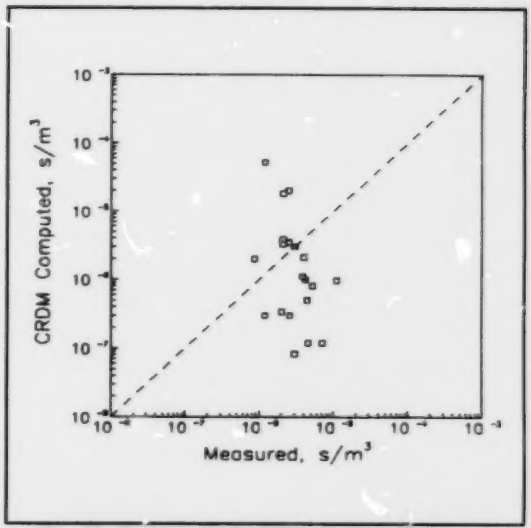
I - Building Wake Effect Included



II - Building Wake Effect Included, Release Height = 0



III - No Building Wake Effect, Release Height = Source



IV - No Building Wake Effect, Release Height = 0

Figure 5

Log-Log plots of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Hydraulic Studies Anemometer/Vane**

PIBAL 50 m

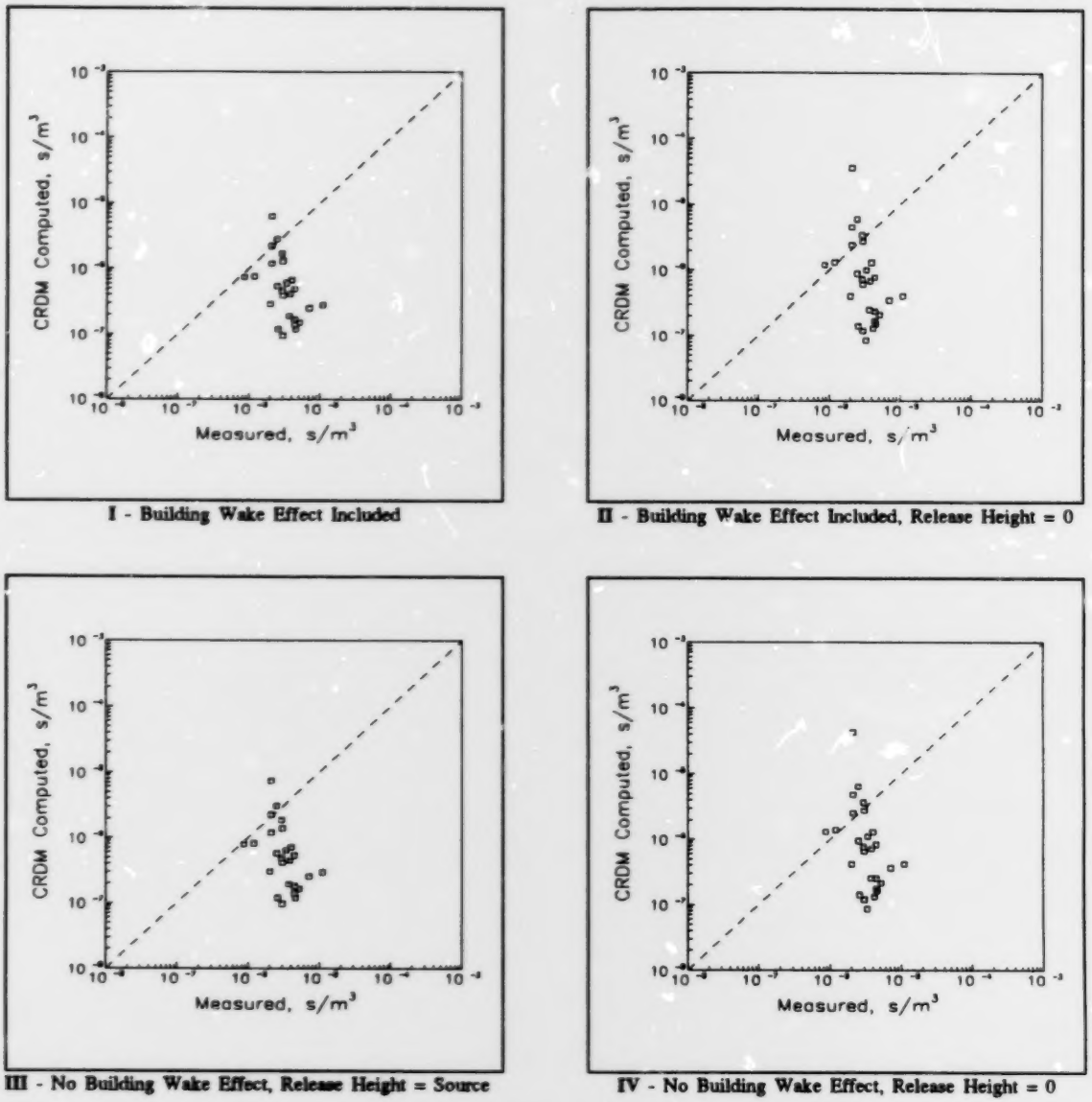

CRDM Computed, s/m³
Measured, s/m³
I - Building Wake Effect Included
II - Building Wake Effect Included, Release Height = 0
III - No Building Wake Effect, Release Height = Source
IV - No Building Wake Effect, Release Height = 0

Figure 6

Log-Log plots of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Pibal at the 50 metre height**

- When CRDM predicts high concentrations it tends to overpredict, and when CRDM predicts low concentrations it tends to underpredict. (see Section 2.3.1.1)

- Inclusion of building wake effect on vertical diffusion or accounting for release height causes a significant (sometimes large) reduction in CRDM predictions. The range of variation is also reduced. Conversely, assuming a surface release (release height = 0) substantially increases some of the CRDM-computed results (as in scenarios II and IV).

- Correction for building wake or source height made the greatest difference for stable conditions (eg, case of Date 041285, Time 1800 in Table 4).

- Correction for building wake or source height had little effect for unstable conditions (eg, case of Date 270586, Time 1200 in Table 4).

- The inclusion of building wake effect on horizontal diffusion introduces a small change in the CRDM-computed results.

- The cases of Date 041285, Times 1700 and 1800, Scenarios II and IV, show the extreme sensitivity of CRDM to input wind speed under stable or near-stable conditions.

Table 5 lists the model performance measures using all the available data for all twenty reference cases. The results show the following:

- The values and trends of the *FB* (fractional bias) and *GM* (geometric mean) are roughly similar for meteorological input from the East Boundary, Inland and Hydraulic Studies sites (wind speed measured at or near 10m height). The *FB* and *GM* are generally in the order IV ≥ II > III ≥ I, simply reflecting the trends in calculated concentrations noted earlier (ie, with no correction to vertical diffusion for building wake or source height, scenarios II and IV, predicted concentrations are significantly higher).

- The *FB* closest to 0 (all data included) was *FB* = -0.13 for scenario I (building wake correction in horizontal and vertical) with meteorological input from the inland tower. The highest percentage of values within a factor of two (50%) occurred for scenarios I and III (corrections to vertical diffusion included) with meteorological input from the Inland Aerovane. The *GM* value closest to unity, *GM* = 0.82, was for scenario IV (no source height or building wake correction) with meteorological input from the East Boundary Aerovane.

- The scatter in all results was, however, large as reflected by the *GSD*. Assuming that the data are log-normally distributed, approximately 95% of values should fall within a factor of the GSD^2 of the *GM*. The *GSD*'s determined here varied between 2.7 and 9.3, corresponding to GSD^2 factors of 7.5 to 87. As will be shown later (Section 2.3.1.1), some of the scatter is accounted for by the variation of model performance with atmospheric stability. The *GM* and *FM* given in Table 5 were calculated for all data points and reflect the fact that most data were gathered under unstable and neutral conditions. Caution should thus be exercised to avoid drawing oversimplistic general conclusions from Table 5.

TABLE 5

PERFORMANCE MEASURES - ALL DATA

MET LOCATION (# of data points)	EAST BOUNDARY (28)				INLAND (16)				MICROWAVE (16)				HYDRAULIC (20)				PIBAL (27)			
SCENARIO	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
FB	-0.73	1.26	-0.55	1.44	-0.13	1.71	0.19	1.78	-1.51	-1.42	-1.57	-1.37	-0.79	0.33	-0.67	0.48	-1.20	-0.37	-1.14	-0.26
NMSE	2.6	40.7	2.6	62.5	2.1	58.4	2.8	83.3	8.5	5.6	7.5	5.1	2.9	7.0	2.8	8.6	4.2	6.4	3.9	7.6
% within factor of 2	29	36	29	43	50	38	50	38	0	19	0	25	25	55	35	25	22	19	22	19
GM (C_p/C_o)	0.34	0.76	0.36	0.82	0.66	1.67	0.76	2.12	0.09	0.11	0.09	0.11	0.26	0.42	0.28	0.45	0.15	0.22	0.16	0.23
GSD (C_p/C_o)	3.40	5.96	3.60	6.69	3.38	8.44	3.83	9.35	2.74	3.32	2.88	3.47	5.07	7.62	5.34	8.01	4.07	5.50	4.18	5.67

- Scatter in results (as indicated by the *GSD* and the *NMSE*) was generally much higher for scenarios II and IV (corrections to vertical diffusion for building wake or release height not included) than for scenarios I and III (corrections to vertical diffusion included)

- Model calculations using input data from the Microwave Tower and the PIBAL generally underpredicted measured concentrations (negative *FB* values and *GM* << 1). This is likely partially due to the fact that wind speeds measured at 50m may overestimate the representative wind speed experienced by the plume.

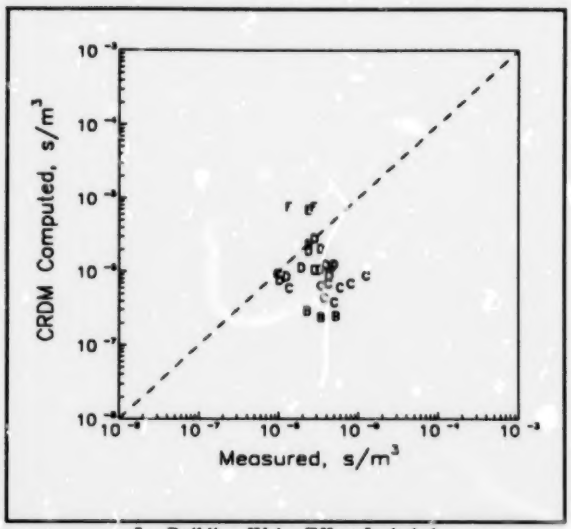
2.3.1.1 Results by Stability Class

The results shown in Figures 2 - 6 for the least conservative and most conservative scenarios (I and IV respectively) were replotted in Figures 7 - 11. In these figures, the data points are labelled by atmospheric stability categories ranging from A to F determined from Monin-Obukhov lengths, L, as calculated by CRDM (Category A represents extremely unstable conditions, D neutral conditions and F extremely stable conditions). The plots clearly show the consistent trend of CRDM in underpredicting measured dilution factors for unstable atmospheric conditions (A, B, C) and overestimating for stable mixing conditions (E, F). Agreement between CRDM-modelled results and measured data is shown to be reasonable for neutral (D) cases.

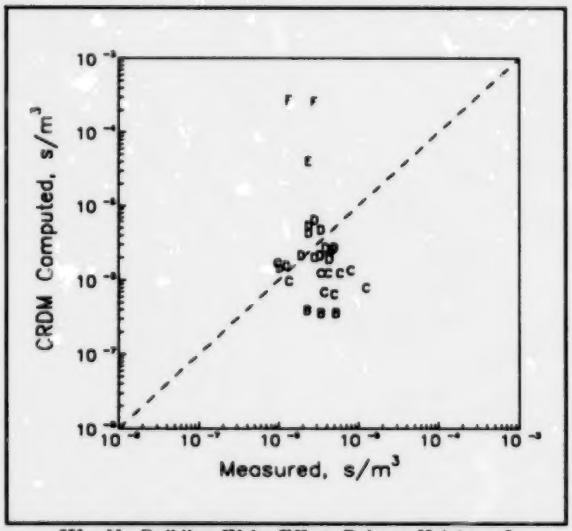
Further, Tables 6a and 6b list the performance measures for all twenty cases under unstable, neutral and stable mixing situations. These results also demonstrate the tendency of the CRDM model to underpredict in unstable atmospheric dispersion conditions (all the *FB* values are negative and the GM ratios are much less than unity). Reasonable agreement between CRDM-computed results and measured data for neutral conditions is illustrated by the *GM* values which are closer to unity and by the higher percentage within a factor of two. For example, the *GM* = 1.01 and 77% of the measured data is predicted to within a factor of two by the model for the East Boundary Aerovane with scenario IV. Low values for the *NMSE*, *FB* and *GSD*, plus *GM* values close to 1.0, are also recorded for these cases.

Only three data points were available for stable conditions due to the low frequency of stable conditions associated with onshore winds at the Darlington site during the study period (Nov/Dec 1985 and May/June 1986). Therefore detailed statistical analysis of the type presented in Table 6a was not carried out. The model always overpredicted concentrations for stable conditions. To give an idea of the extent of model overprediction, *GM* values of C_p/C_o were 3.5, 50.0, 4.7 and 68.0 for scenarios I, II, III and IV, respectively, using meteorological input from the East Boundary Aerovane (see Table 6b). Under stable conditions, therefore, the extent of model overprediction was far greater with no correction to vertical diffusion for building wake or release height (scenarios II and IV).

EAST BOUNDARY AEROVANE



I - Building Wake Effect Included

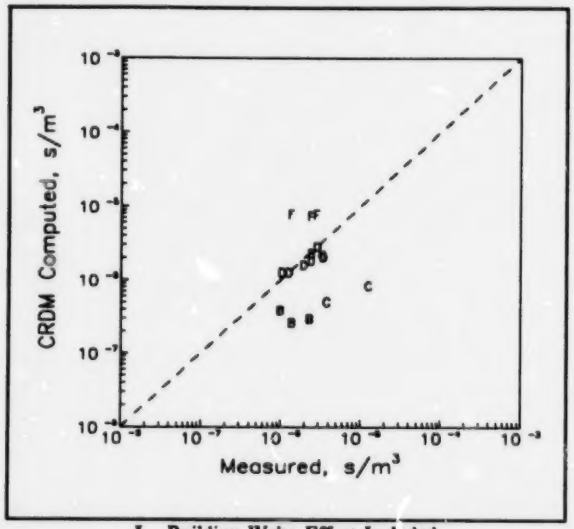


IV - No Building Wake Effect, Release Height = 0

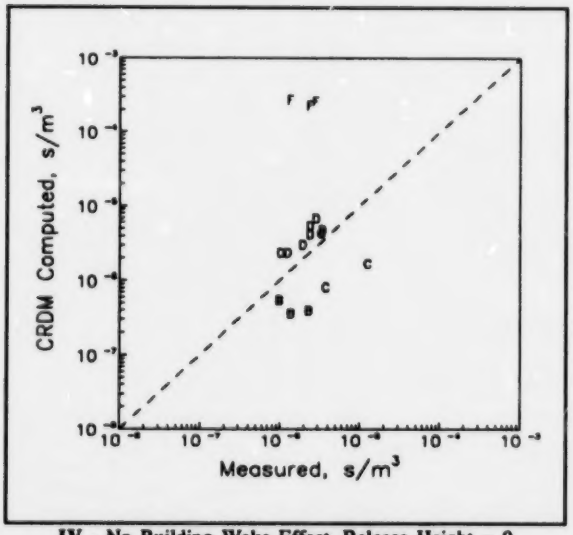
Figure 7

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **East Boundary Aerovane**

INLAND AEROVANE



I - Building Wake Effect Included

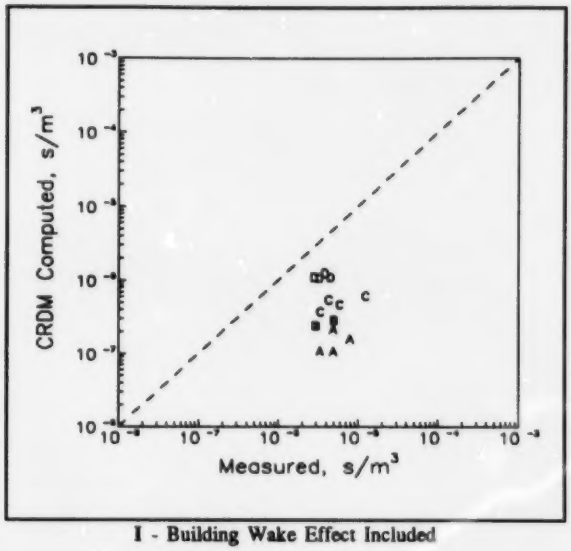


IV - No Building Wake Effect, Release Height = 0

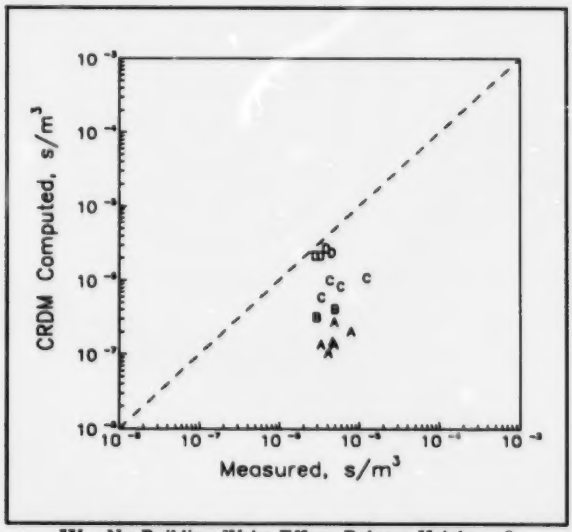
Figure 8

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Inland Aerovane Aerovane**

MICROWAVE TOWER AEROVANE



I - Building Wake Effect Included

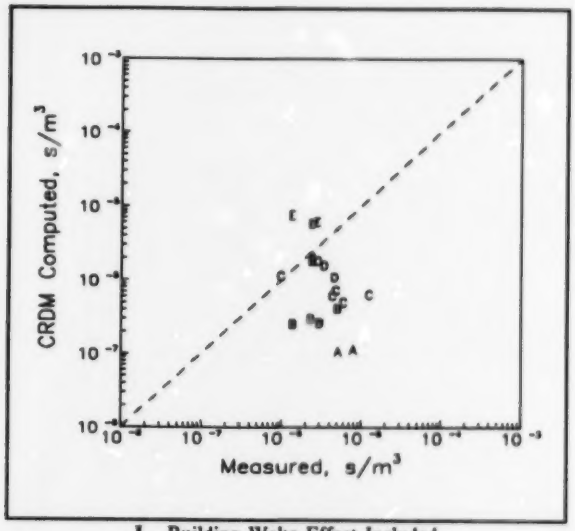


IV - No Building Wake Effect, Release Height = 0

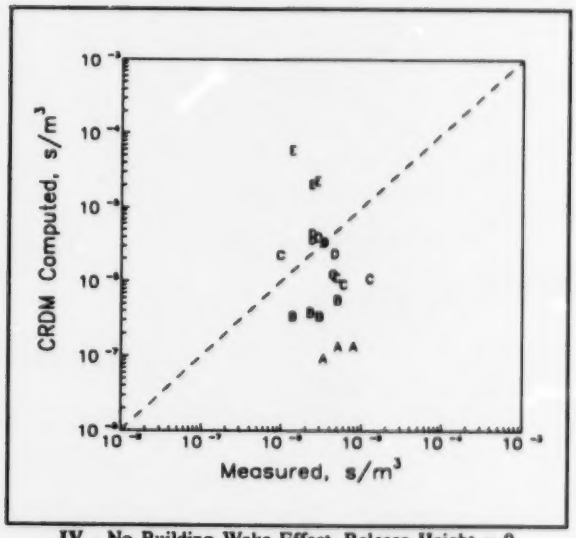
Figure 9

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Microwave Tower Aerovane**

HYDRAULIC STUDIES ANEMOMETER/VANE



I - Building Wake Effect Included

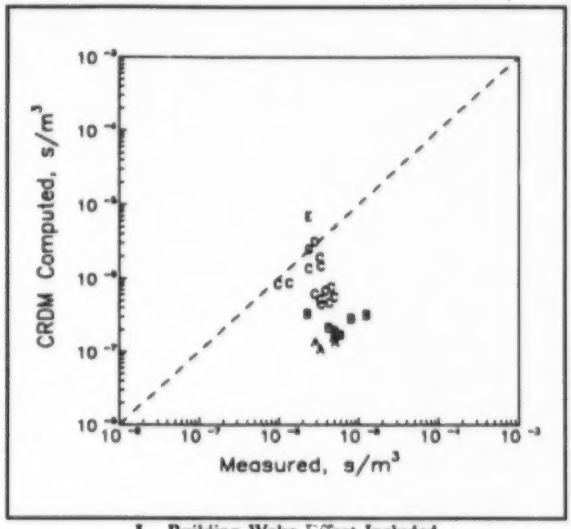


IV - No Building Wake Effect, Release Height = 0

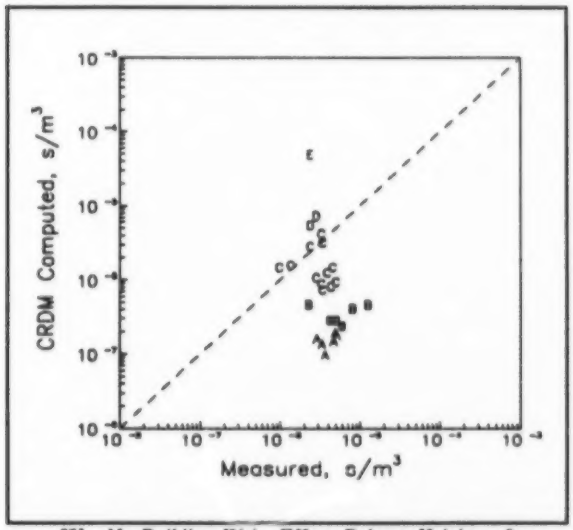
Figure 10

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Hydraulic Studies Anemometer/Vane**

PIBAL 50 m



I - Building Wake Effect Included



IV - No Building Wake Effect, Release Height = 0

Figure 11

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors using wind speed from the **Pibal at the 50 metre height**

TABLE 6a

PERFORMANCE MEASURES - DATA DIVIDED ACCORDING TO ATMOSPHERIC STABILITY

UNSTABLE CONDITIONS

MET LOCATION SCENARIOS (# of data points)	EAST BOUNDARY I (12)	II (12)	III (12)	IV (12)	INLAND I (6)	II (6)	III (6)	IV (6)	MICROWAVE I (10)	II (12)	III (10)	IV (12)	HYDRAULIC I (11)	II (12)	III (11)	IV (12)	PIBAL I (22)	II (24)	III (22)	IV (24)
FB	-1.57	-1.33	-1.55	-1.34	-1.38	-1.03	-1.35	-0.99	-1.78	-1.71	-1.78	-1.70	-1.65	-1.49	-1.64	-1.47	-1.52	-1.28	-1.50	-1.25
NMSE	9.9	5.0	9.1	5.5	8.6	4.3	8.1	4.0	19.9	13.5	19.0	12.8	13.2	7.9	12.5	7.6	8.3	4.7	7.7	4.4
% within factor of 2	8	17	8	17	17	33	17	33	0	0	0	0	9	0	9	0	18	21	18	21
GM (C_p/C_o)	0.13	0.22	0.14	0.21	0.20	0.30	0.21	0.32	0.05	0.06	0.05	0.06	0.09	0.12	0.10	0.13	0.11	0.15	0.12	0.15
GSD (C_p/C_o)	2.34	2.38	2.34	2.58	2.29	2.33	2.27	2.32	1.91	2.17	1.94	2.21	3.21	3.68	3.29	3.75	3.21	3.86	3.27	3.94

NEUTRAL CONDITIONS

MET LOCATION SCENARIOS (# of data points)	EAST BOUNDARY I (13)	II (13)	III (13)	IV (13)	INLAND I (7)	II (7)	III (7)	IV (7)	MICROWAVE I (4)	II (4)	III (4)	IV (4)	HYDRAULIC I (5)	II (5)	III (5)	IV (5)	PIBAL I (2)	II (2)	III (2)	IV (2)
FB	-0.71	-0.06	-0.62	0.03	-0.15	0.52	-0.04	0.63	-1.05	-0.53	-0.94	-0.43	-0.60	0.08	-0.55	0.14	-	-	-	-
NMSE	0.99	0.39	0.83	0.38	0.08	0.38	0.06	0.55	1.61	0.35	1.22	0.22	0.64	0.21	0.54	0.21	-	-	-	-
% within factor of 2	54	77	54	77	100	71	100	57	0	75	0	100	60	80	80	100	-	-	-	-
GM (C_p/C_o)	0.48	0.91	0.53	1.01	0.89	1.72	0.99	1.92	0.32	0.58	0.36	0.66	0.54	1.10	0.58	1.16	-	-	-	-
GSD (C_p/C_o)	1.75	1.77	1.75	1.75	1.26	1.24	1.26	1.23	1.22	1.38	1.22	1.17	1.66	1.68	1.60	1.65	-	-	-	-

TABLE 6b

PERFORMANCE MEASURES - DATA DIVIDED ACCORDING TO ATMOSPHERIC STABILITY

STABLE CONDITIONS

NOTE: There were only 3 data points for stable conditions for the East Boundary and Inland Aerovanes and for the Hydraulic Studies Anemometer/Vane. The model overpredicted in all these cases.

MET LOCATION SCENARIO (# of data points)	EAST BOUNDARY I (3)	II (3)	III (3)	IV (3)	INLAND I (3)	II (3)	III (3)	IV (3)	MICROWAVE I	II	III	IV	HYDRAULIC I (3)	II (3)	III (3)	IV (3)	PIBAL I	II	III	IV
GM (C_p/C_o)	3.51	49.5	4.74	68.0	3.64	86.5	5.76	120.0	-	-	-	-	3.06	12.0	3.72	14.3	-	-	-	-
GSD (C_p/C_o)	1.44	1.44	1.45	1.47	1.45	1.48	1.44	1.47	-	-	-	-	1.59	2.29	1.59	2.32	-	-	-	-

90-200

2.3.2 Lateral Plume Spread

Results for the measured and CRDM-computed lateral plume spreads, σ_y, are summarized in Figures 12 - 16. These figures contain the log-log plots of the lateral plume spreads for the least conservative and most conservative scenarios for each of the five meteorological sites. The atmospheric stability categories are also indicated. These plots show that the model predicts a narrower plume than is observed in all stable situations. Under unstable mixing conditions, CRDM frequently overpredicts the lateral plume spread. Results vary for neutral conditions. In general, the results indicate that σ_y at the site boundary varies less with stability than predicted by the Briggs' correlation.

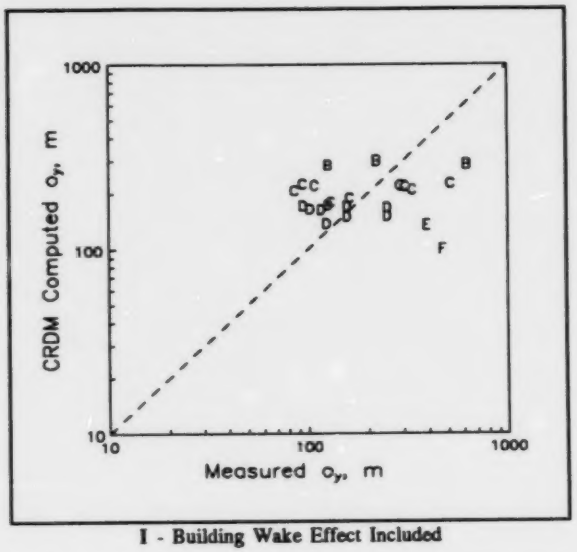
2.3.3 Plume Profiles

Measured and CRDM-computed plume profiles from December 12, 1985 (1800 hrs), June 16, 1986 (1300 hrs) and June 26, 1986 (1100 hrs) are illustrated in Figures 17, 18 and 19 respectively. The plume profile from December 12 is an example of stable atmospheric conditions. Figure 17 shows that CRDM predicts a narrow plume and hence would tend to overestimate the measured maximum ground-level concentration (glc). The observed data shows a much wider plume where it is difficult to distinguish a specific plume direction. This is indicative of plume meander in a stable situation. The East Boundary Aerovane predicted the plume direction better than the Inland Aerovane and Hydraulic Studies Anemometer/Vane sites. A neutral case is shown in Figure 18. The maximum glc was estimated reasonably well by CRDM and the plume direction was indicated fairly well by all three meteorological sites (East Boundary Aerovane, Microwave Tower Aerovane and PIBAL). For an unstable situation as shown in Figure 19, the model underestimated the observed maximum glc, although the shape of the plume was described well, which indicates that the extent of vertical diffusion was overpredicted. Although not the case in this example, CRDM typically overpredicted the plume width in unstable cases (and therefore underestimated the maximum glc). Figure 19 shows that the PIBAL wind direction measurement at the height of 50 metres was a good indicator of plume direction.

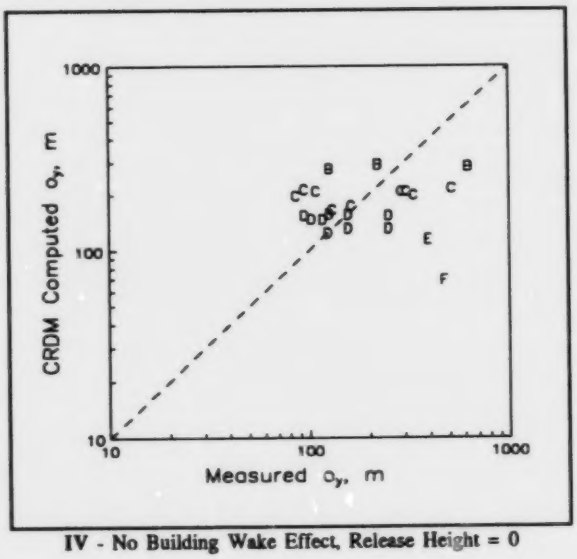
2.4 Results Using Default σ_θ

For unstable atmospheric conditions, CRDM typically predicted a larger lateral plume spread (σ_y) than was observed during the Darlington tracer study and for stable conditions, CRDM predicted a smaller plume spread than observed. The preferred method of calculating σ_θ was not available as σ_θ was not measured during the Darlington tracer study. The alternate method of deriving a stability class from L and z_o and using the appropriate Brigg's formula was therefore used (Section 1.3) in the absence of measured σ_θ values. However, past studies (Chen, 1986) have shown that σ_θ is greater than 0.1 for 95% of the time at Port Hope which is also located on the north shore of Lake Ontario, about 25 km east of Darlington NGS. A default assumption of σ_θ = 0.1 would thus be reasonable and conservative. Therefore the scenarios involving no building wake effect (III - release height = H_B, IV - release height = 0) were rerun using the East Boundary Aerovane wind data and a default value of σ_θ = 0.1.

EAST BOUNDARY AEROVANE



I - Building Wake Effect Included

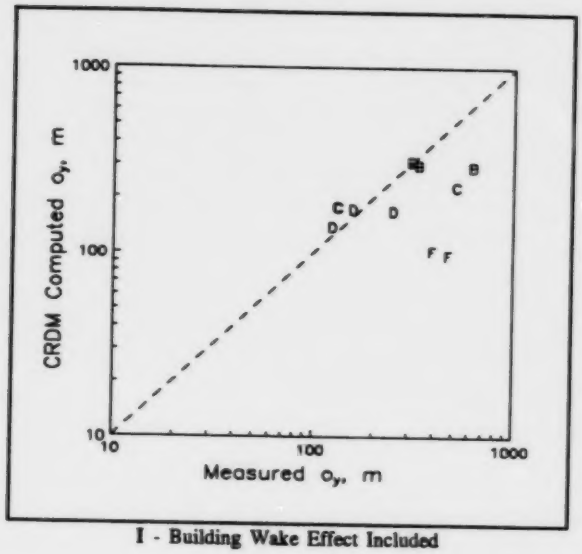


IV - No Building Wake Effect, Release Height = 0

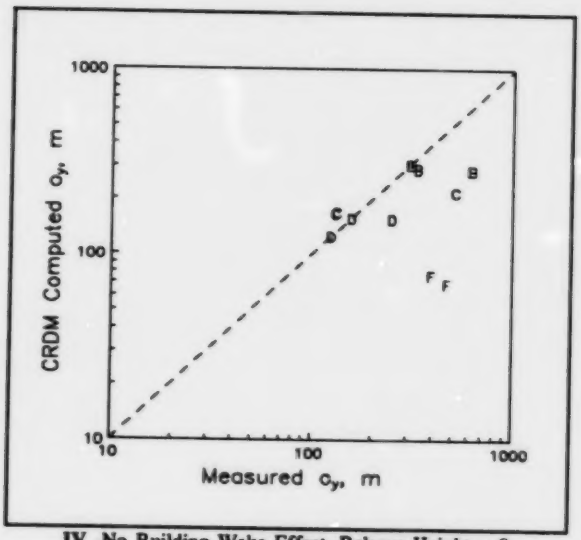
Figure 12

Log-Log plots, showing stability categories, of the measured and CRDM-computed lateral plume spread, σ_y, using wind speed from the **East Boundary Aerovane**

INLAND AEROVANE



I - Building Wake Effect Included

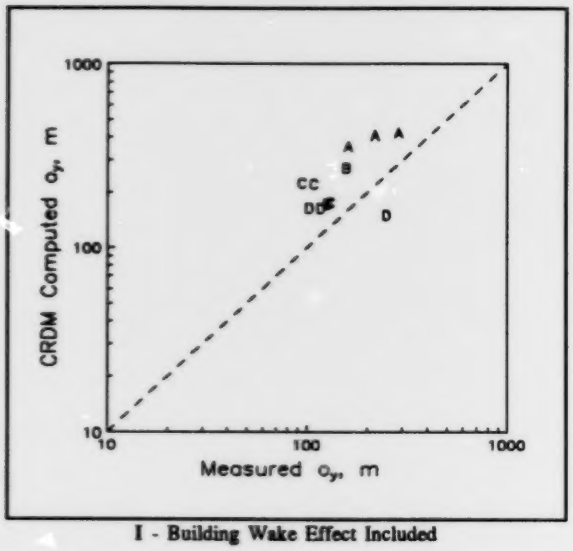


IV -No Building Wake Effect, Release Height = 0

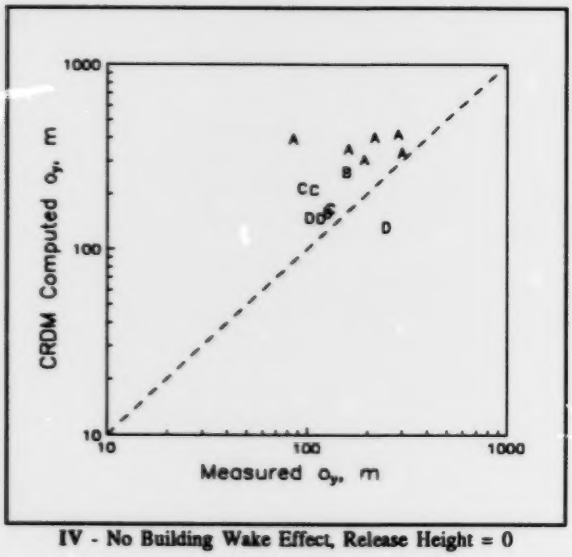
Figure 13

Log-Log plots, showing stability categories, of the measured and CRDM-computed lateral plume spread, σ_y, using wind speed from the **Inland Aerovane**

MICROWAVE TOWER AEROVANE



I - Building Wake Effect Included

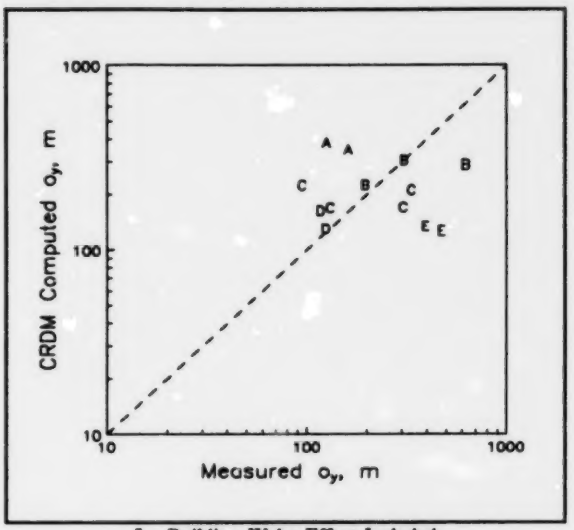


IV - No Building Wake Effect, Release Height = 0

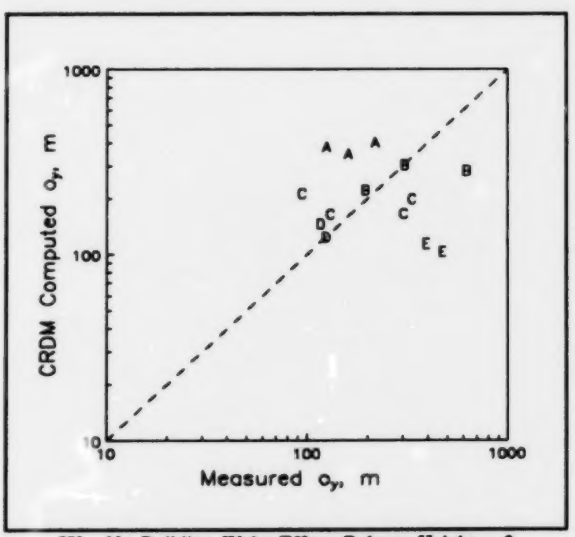
Figure 14

Log-Log plots, showing stability categories, of the measured and CRDM-computed lateral plume spread, σ_y, using wind speed from the **Microwave Tower Aerovane**

HYDRAULIC STUDIES ANEMOMETER/VANE



I - Building Wake Effect Included

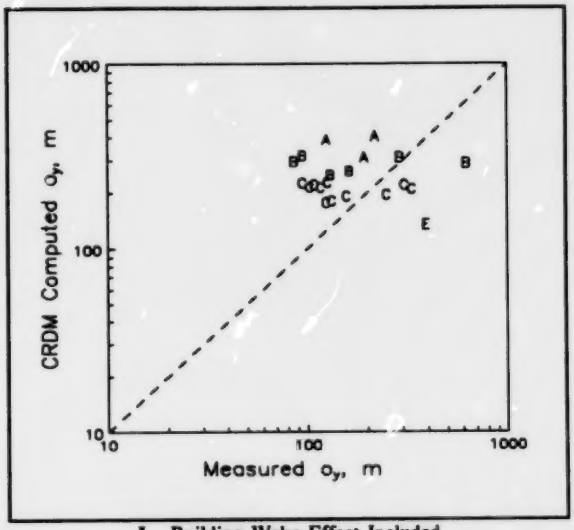


IV - No Building Wake Effect, Release Height = 0

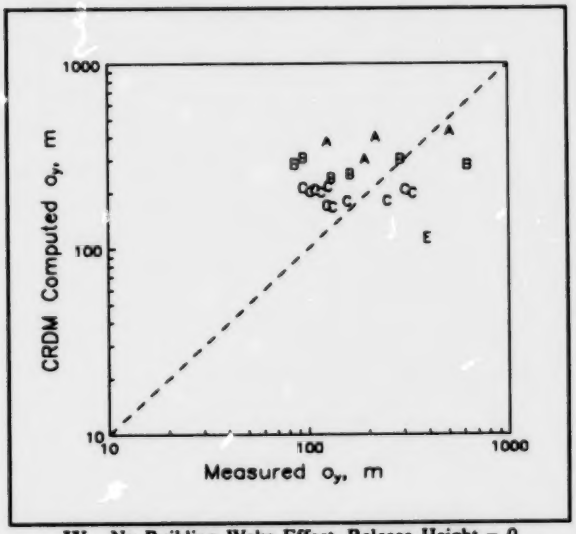
Figure 15

Log-Log plots, showing stability categories, of the measured and CRDM-computed lateral plume spread, σ_y, using wind speed from the **Hydraulic Studies Anemometer/Vane**

PIBAL 50 m



I - Building Wake Effect Included



IV - No Building Wake Effect, Release Height = 0

Figure 16

Log-Log plots, showing stability categories, of the measured and CRDM-computed lateral plume spread, σ_y, using wind speed from the **Pibal at the 50 metre height**

PLUME PROFILE - STABLE

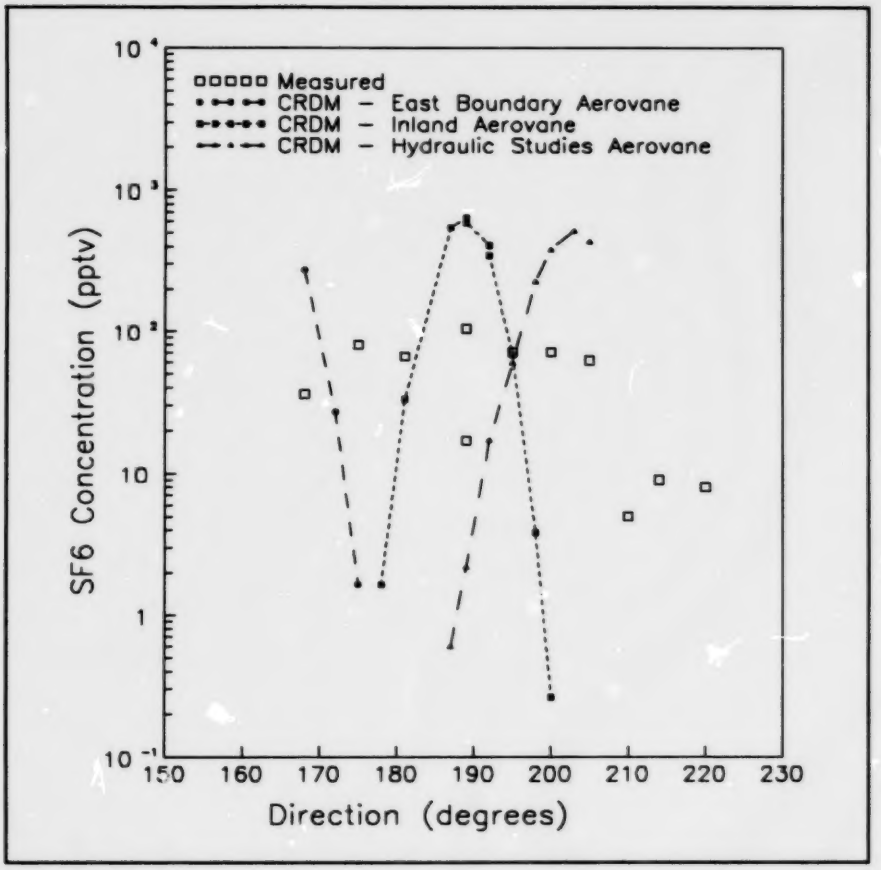


Figure 17

Measured and CRDM-computed plume profiles (one-hour average) at the site boundary at 1800 hours, December 12, 1985. The direction given is the bearing looking from the measurement point towards the release point.

PLUME PROFILE - NEUTRAL

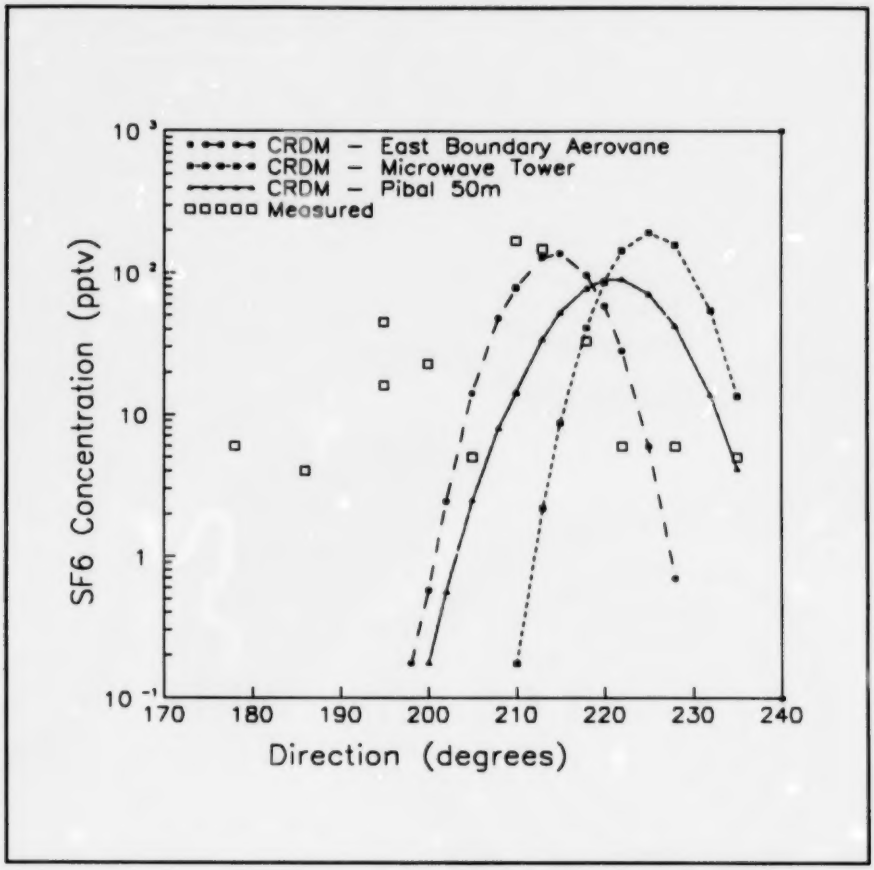


Figure 18

Measured and CRDM-computed plume profiles (one-hour average) at the site boundary at 1300 hours, June 16, 1986. The direction given is the bearing looking from the measurement point towards the release point.

PLUME PROFILE - UNSTABLE

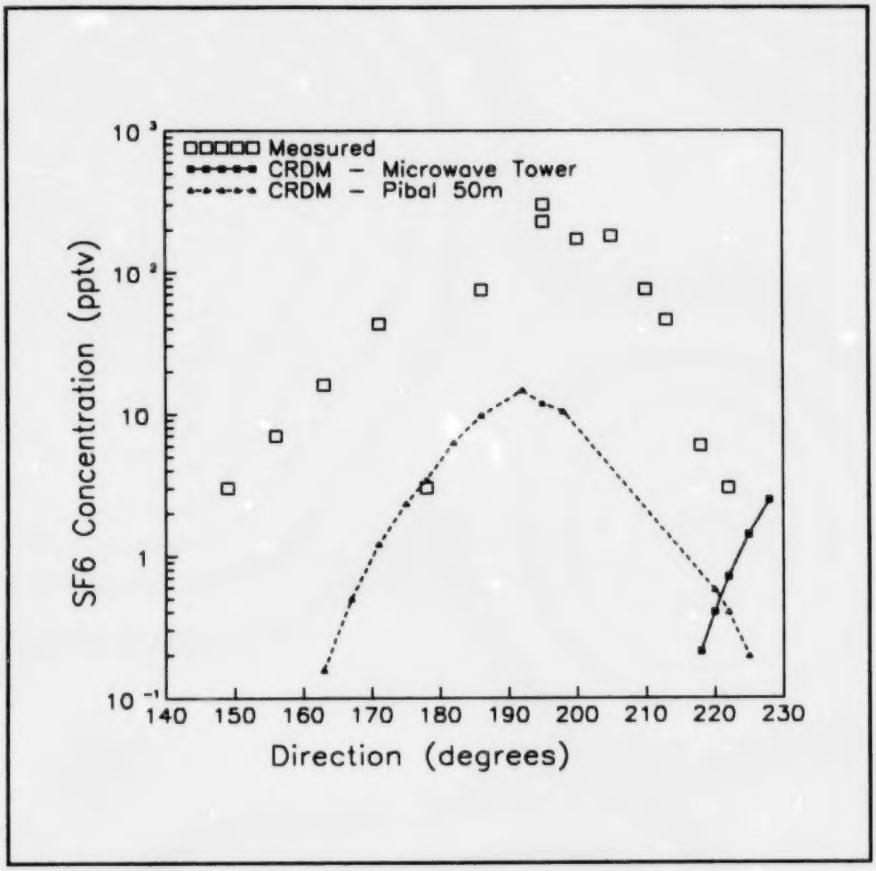


Figure 19

Measured and CRDM-computed plume profiles (one-hour average) at the site boundary at 1100 hours, June 26, 1986. The direction given is the bearing looking from the measurement point towards the release point.

Figure 20 shows a comparison of the observations to the CRDM-computed results with and without the incorporation of the default value of 0.1 for σ_θ for scenario III. Similarly, Figure 21 displays the results for scenario IV. These plots illustrate the change introduced by deriving σ_y from σ_θ where $\sigma_\theta = 0.1$. The dilution factors for the unstable situations (A, B, C) were still underpredicted, but less severely. The model tended to slightly overpredict for neutral conditions. In these situations, the default value of $\sigma_\theta = 0.1$ produced a slightly narrower plume and hence raised the maximum centreline dilution factor. For the stable cases, the plume width was still underestimated, especially for scenario IV (Release Height = 0). This contributed to overprediction of the maximum centreline dilution factor. Using $\sigma_\theta = 0.1$ only slightly decreased the estimation of maximum centreline dilution factor for stable cases. A higher value of σ_θ would, of course, reduce the CRDM-modelled dilution factors for stable atmospheric conditions.

Statistical measures are listed in Table 7. The relevant results from Table 6a are repeated for comparison purposes. The *FB* indicates tendency of the Briggs' formula to underpredict plume width at the site, except for neutral conditions under scenario IV. The incorporation of a default σ_θ value decreased the scatter of the data (a smaller *NMSE* and *GSD*) in every case, except for scenario IV under neutral conditions. The percentage of results within a factor of 2 improved to 33% (from 17%) for unstable conditions under scenario IV. Also the percentage increased to 77% from 54% under scenario III for neutral situations.

3.0 CONCLUSIONS AND RECOMMENDATIONS

A comparison of the CRDM results with field data from the Darlington Tracer Study has been carried out. An estimation of model performance using this data has been obtained and meteorological scenarios which lead to error in model output have been identified. The following are conclusions drawn from the results presented in the previous section. Recommendations for improvement in model performance are also given.

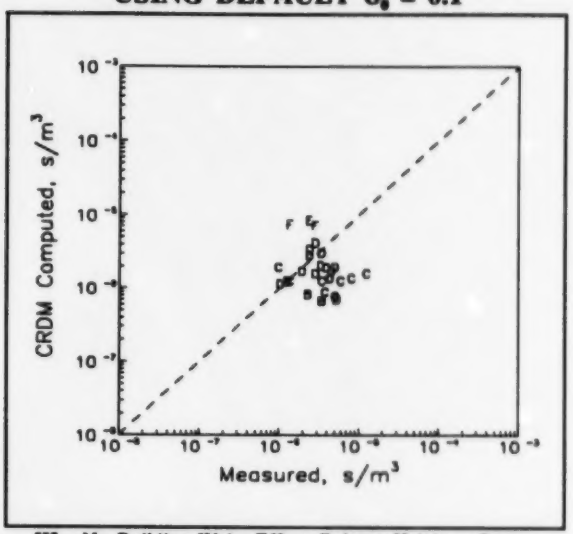
One general observation that was noted in this study is related to calculation of model performance measures. Performance statistics must always be considered along with a visual presentation of results and a good understanding of the model being evaluated. Model trends may not always be apparent though a statistical evaluation. An example of this was the evaluation of model performance using all data points which masked the fact that model performance varied greatly with atmospheric stability.

The maximum dilution factors measured during the Darlington tracer study exhibited a variation of little more than an order of magnitude and demonstrated very little sensitivity to atmospheric stability conditions. The CRDM-computed results, in contrast, ranged over 3 orders of magnitude.

Plots of the observed data versus CRDM-computed results, and calculation of performance measures, by stability category, both showed the following trends:

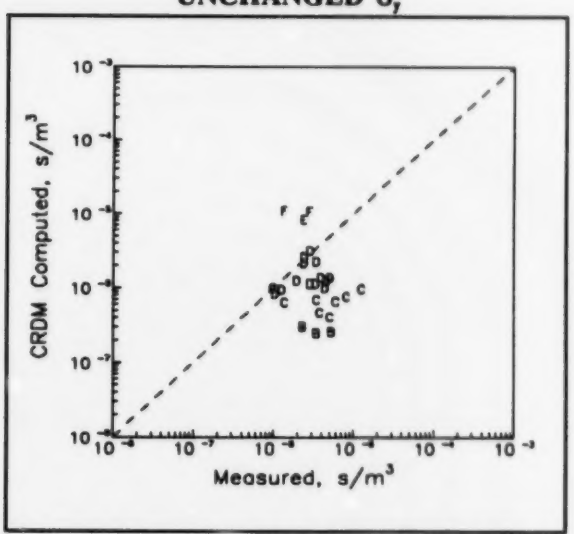
EAST BOUNDARY AEROVANE

USING DEFAULT σ_θ = 0.1



III - No Building Wake Effect, Release Height = Source

UNCHANGED σ_θ



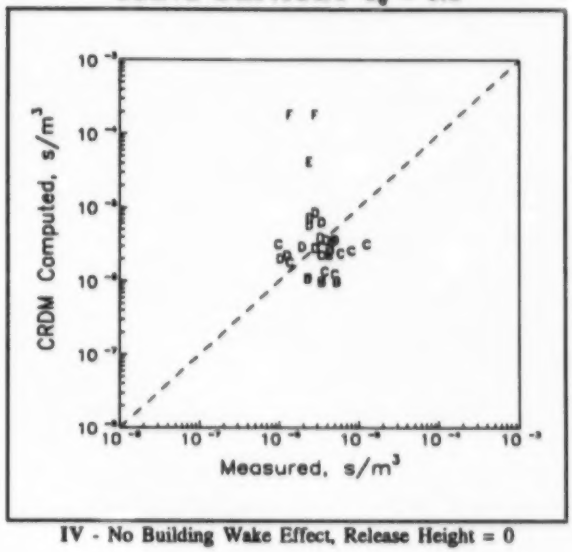
III - No Building Wake Effect, Release Height = Source

Figure 20

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors and comparing results with and without σ_θ = 0.1 using wind speed from the East Boundary Aerovane

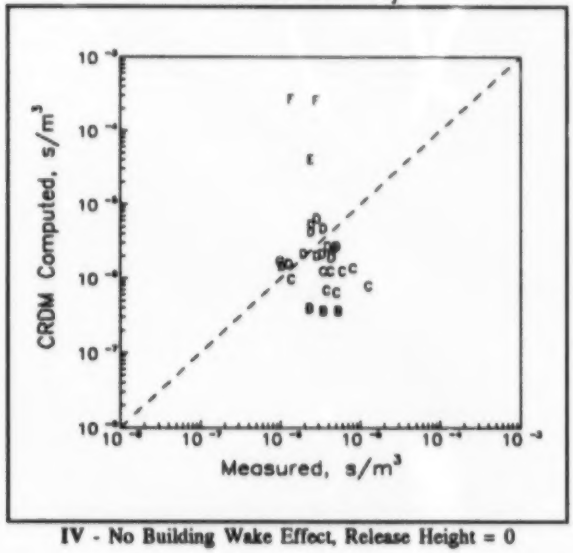
EAST BOUNDARY AEROVANE

USING DEFAULT σ_θ = 0.1



IV - No Building Wake Effect, Release Height = 0

UNCHANGED σ_γ



IV - No Building Wake Effect, Release Height = 0

Figure 21

Log-Log plots, showing stability categories, of the measured and CRDM-computed maximum ground-level dilution factors and comparing results with and without σ_θ = 0.1 using wind speed from the East Boundary Aerovane

TABLE 7

MODEL RUNS - EAST BOUNDARY AEROVANE
PERFORMANCE MEASURES

USING σ_θ = 0.1

MIXING CONDITIONS (# of data points)	ALL (28)		UNSTABLE (12)		NEUTRAL (13)	
SCENARIO	III	IV	III	IV	III	IV
FB	-0.43	1.31	-1.21	-0.82	-0.32	0.34
NMSE	1.63	37.7	3.94	1.68	0.43	0.52
% within factor of 2	43	46	17	33	77	77
GM (C_p/C_o)	0.59	1.30	0.29	0.47	0.73	1.41
GSD (C_p/C_o)	2.76	4.80	2.27	2.23	1.69	1.73

FROM TABLE 6a

MIXING CONDITIONS (# of data points)	ALL (28)		UNSTABLE (12)		NEUTRAL (13)	
SCENARIO	III	IV	III	IV	III	IV
FB	-0.55	1.44	-1.55	-1.34	-0.62	0.03
NMSE	2.6	62.5	9.1	5.5	0.83	0.38
% within factor of 2	29	43	8	17	54	77
GM (C_p/C_o)	0.38	0.82	0.14	0.21	0.53	1.01
GSD (C_p/C_o)	3.60	6.69	2.34	2.58	1.75	1.75

- CRDM underpredicted the observed data for unstable atmospheric dispersion conditions;

- CRDM overestimated the measurements in every case for stable mixing conditions;

- CRDM-computed results and measured data for neutral conditions agreed reasonably well.

Meteorological input data from five locations within and nearby the Darlington NGS site were used with the model, and sometimes gave significantly different results indicating the importance of inputting a wind speed representative of that experienced by the plume. The high sensitivity of the model to input wind speed at low wind speed values observed here was demonstrated previously by sensitivity analysis (Camacho, 1987).

In general, the results suggest that a source height correction (or correction for enhanced vertical diffusion due to building wake effects) should always be included in CRDM to avoid severe overprediction of site-boundary dilution factors under stable conditions. An atmospheric stability based prediction of σ_y, the lateral standard deviation of the plume, seems to be unsuitable. Even the simple default assumption that $\sigma_\theta = 0.1$ gave better model performance. Unfortunately, data were not available to evaluate the preferred option of basing σ_y on measured σ_θ values. However, for physical reasons this method should give an accurate measure of lateral plume diffusion. The addition of a correction for enhanced horizontal diffusion due to building wake effects made little improvement in model predictions. The model underpredicted concentrations during nominally unstable conditions. This suggests that a transition region exists for some distance between the stable or neutral air over the lake and the fully developed unstable conditions occurring further inland. Consideration should be given to modifying the way in which the model determines stability when considering dispersion over short distances (a few km) inland. Nonetheless, it should be noted that unstable conditions correspond to highest dilution (ie, lowest concentrations) and model underprediction in this case is potentially much less serious than it would be under stable (ie, worst-case) dispersion conditions where the model tends to overpredict concentrations. The data from the Darlington tracer study also suggested that the terrain encountered by the plume (which is plume-direction dependent) had a significant effect on plume dilution. Models such as CRDM, cannot treat such larger-scale terrain effects, even though surface roughness is accounted for.

It is recommended that the current procedure used in CRDM to calculate σ_y in the absence of measured σ_θ values (which is based on empirical σ_y curves and a stability class derived from L and z_o) be altered. It is preferable to use a default value of 0.1 for σ_θ and then derive σ_y. This modification does not require a programming change to the code. By including the default value for σ_θ (=0.1) in the default input data file, CRDM will automatically adjust to using this scheme.

Approved by:

D.J.R. Dodd
Manager
Chemical Research Department

Prepared by:

S.C. Wright
Computer Scientist
Environmental Science Section

Reviewed by:

for O.T. Melo
Supervising Engineer
Environmental Science Section

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